

Inclusive production of a pair of identified, rapidity-separated hadrons in proton collisions

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Abstract. We consider the inclusive process where a pair of identified hadrons having large transverse momenta is produced in high-energy proton-proton collisions. We concentrate on the kinematics where the two identified hadrons in the final state are separated by a large interval of rapidity. In this case the cross section receives large higher-order corrections, which can be resummed in the BFKL approach. We provide a theoretical input for the resummation of such contributions with next-to-leading logarithmic accuracy. This process has much in common with the widely discussed Mueller-Navelet jets production and can be also used to access the BFKL dynamics at proton colliders.

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INTRODUCTION

We consider the semi-inclusive process

$$\text{proton}(p_1) + \text{proton}(p_2) \rightarrow \text{hadron}_1(k_1) + \text{hadron}_2(k_2) + X. \quad (1)$$

in the kinematics where the identified hadrons in the final state, h_1, h_2 , have large transverse momenta, $\vec{k}_1^2 \sim \vec{k}_2^2 \gg \Lambda_{\text{QCD}}^2$, and are separated by a large interval of rapidity $\Delta y \gg 1$ at $s = 2p_1 \cdot p_2 \gg \vec{k}_{1,2}^2$. This process has much in common with the widely discussed Mueller-Navelet jet production [1] and can be also used to access the BFKL dynamics [2] at proton colliders.

In QCD collinear factorization the cross section of the process reads

$$\frac{d\sigma}{dy_1 dy_2 d^2k_1 d^2k_2} = \sum_{i,j=q,\bar{q},g} \int_0^1 \int_0^1 dx_1 dx_2 f_i(x_1, \mu_F) f_j(x_2, \mu_F) \frac{d\hat{\sigma}(x_1 x_2 s, \mu_F)}{dy_1 dy_2 d^2k_1 d^2k_2}, \quad (2)$$

where the i, j -indices specify parton types, $i, j = q, \bar{q}, g$, $f_i(x, \mu_F)$ denotes the initial protons parton density functions (PDFs), the longitudinal fractions of the partons involved in the hard subprocess are $x_{1,2}$, μ_F is the factorization scale and $d\hat{\sigma}(x_1 x_2 s, \mu_F)$ is the partonic cross section for the production of identified hadrons. The latter is expressed in terms of parton fragmentation functions (FFs). The FF describes the probability of the inclusive fragmentation of the parton i into a hadron h . The cross section is generically

expressed as follows

$$d\sigma_i = C_i^h(z)dz \rightarrow d\sigma^h = d\alpha_h \int_{\alpha_h}^1 \frac{dz}{z} D_i^h\left(\frac{\alpha_h}{z}, \mu_F\right) C_i^h(z, \mu_F), \quad (3)$$

where C_i^h is the cross section (calculable in QCD perturbation theory) for the production of a parton with momentum fraction z ; the non-perturbative, large-distance part of the transition to a hadron with momentum fraction α_h is described in terms of the fragmentation function D_i^h ; μ_F stands here for the factorization scale.

In the considered Regge limit the partonic cross section can be calculated in the BFKL approach. Generically in BFKL the total cross section $A + B \rightarrow X$ can be written as

$$\sigma_{AB} = \frac{1}{(2\pi)^2} \int \frac{d^2 q_1}{\vec{q}_1^2} \Phi_A(\vec{q}_1, s_0) \int \frac{d^2 q_2}{\vec{q}_2^2} \Phi_B(-\vec{q}_2, s_0) \int_{\delta-i\infty}^{\delta+i\infty} \frac{d\omega}{2\pi i} \left(\frac{s}{s_0}\right)^\omega G_\omega(\vec{q}_1, \vec{q}_2). \quad (4)$$

This factorization is valid both in the leading logarithmic approximation (LLA), which means resummation of all terms $(\alpha_s \ln s)^n$, and in the next-to-LLA (NLA), which means resummation of all terms $\alpha_s (\alpha_s \ln s)^n$. The Green's function G_ω is process-independent and is determined through the BFKL equation whose kernel is known in the NLA [3]. As for the process-dependent impact factors (IFs) $\Phi_{A,B}$, only very few have been calculated in the NLA. Below we discuss our recent calculation [4] of the identified-hadron impact factor which is necessary for the NLA analysis of the process (1).

We calculate the projection of the impact factor on the eigenfunctions of LO BFKL kernel, i.e. the impact factor in the so called (ν, n) -representation,

$$\Phi(\nu, n) = \int d^2 q \frac{\Phi(\vec{q})}{\vec{q}^2} \frac{1}{\pi\sqrt{2}} (\vec{q}^2)^{i\nu-\frac{1}{2}} e^{in\phi}. \quad (5)$$

Here ϕ is the azimuthal angle of the vector \vec{q} counted from some fixed direction in the transverse space. This (ν, n) -representation is the most convenient one in view of the numerical determination of the cross section of process (1).

THE IDENTIFIED HADRON IMPACT FACTOR

The starting point for our NLA calculation is provided by the IFs for colliding partons [5]. In LLA quark and gluon IFs have the form (N is the number of QCD colors)

$$\Phi_q = g^2 \frac{\sqrt{N^2-1}}{2N}, \quad \Phi_g = \frac{C_A}{C_F} \Phi_q, \quad C_A = N, \quad C_F = \frac{N^2-1}{2N}. \quad (6)$$

For the identified-hadron LLA IF in the (ν, n) -representation we obtain the result

$$\frac{\pi\sqrt{2}\vec{k}^2}{\mathcal{C}} \frac{d\Phi^h(\nu, n)}{d\alpha_h d^2 k} = \int_{\alpha_h}^1 \frac{dx}{x} \left(\frac{C_A}{C_F} f_g(x) D_g^h\left(\frac{\alpha_h}{x}\right) + \sum_{a=q, \bar{q}} f_a(x) D_a^h\left(\frac{\alpha_h}{x}\right) \right) (\vec{k}^2)^{\gamma-\frac{n}{2}} (\vec{k} \cdot \vec{l})^n,$$

where $\gamma = i\nu - \frac{1}{2}$, $\alpha_s = g^2/(4\pi)$, $\mathcal{C} = 2\pi\alpha_s\sqrt{\frac{2C_F}{C_A}}$, while \vec{k} is the transverse momentum of the parton (quark or gluon) which fragments to the hadron h .

Note that for the LLA IF, there can be only a one-particle intermediate state, whereas for the NLA IF, we have to consider virtual corrections to the one-particle intermediate state, and also real particle production, with a two-particle intermediate state. The intermediate steps of our calculation contain ultraviolet and infrared soft and collinear divergences, which are regularized in the dimensional regularization. We have explicitly verified that in the final result for the IF soft and virtual infrared divergences cancel each other, whereas the infrared collinear ones are compensated by the PDFs' and FFs' renormalization counterterms, see [4] for the details. The remaining ultraviolet divergences are taken care of by the renormalization of the QCD coupling, which introduces the dependence on the renormalization scale μ_R .

Another singularity which is present both for the partonic subprocesses initiated by the quark and the gluon PDFs is associated with the real particle production when an extra gluon is present in the intermediate state. It is related to the kinematic region when this extra gluon is emitted in the central rapidity region, away from the fragmentation region of the initial quark/gluon. This contribution of the central region must be subtracted from the impact factor, since it is to be assigned in the BFKL approach to the Green's function, see [6] for the description of this subtraction in details.

Finally, we arrive at our NLA result for the identified-hadron IF

$$\begin{aligned} \vec{k}_h^2 \frac{d\Phi^h(\nu, n)}{d\alpha_h d^2k_h} = & 2\alpha_s(\mu_R) \sqrt{\frac{C_F}{C_A}} (\vec{k}_h^2)^{\gamma - \frac{n}{2}} (\vec{k}_h \cdot \vec{l})^n \left\{ \int_{\alpha_h}^1 \frac{dx}{x} \left(\frac{x}{\alpha_h} \right)^{2\gamma} \left[\frac{C_A}{C_F} f_g(x) D_g^h \left(\frac{\alpha_h}{x} \right) \right. \right. \\ & \left. \left. + \sum_{a=q, \bar{q}} f_a(x) D_a^h \left(\frac{\alpha_h}{x} \right) \right] + \frac{\alpha_s(\mu_R)}{2\pi} \int_{\alpha_h}^1 \frac{dx}{x} \int_{\frac{\alpha_h}{x}}^1 \frac{d\zeta}{\zeta} \left(\frac{x\zeta}{\alpha_h} \right)^{2\gamma} \right. \\ & \times \left[\frac{C_A}{C_F} f_g(x) D_g^h \left(\frac{\alpha_h}{x\zeta} \right) C_{gg}(x, \zeta) + \sum_{a=q, \bar{q}} f_a(x) D_a^h \left(\frac{\alpha_h}{x\zeta} \right) C_{qq}(x, \zeta) \right. \\ & \left. \left. + \sum_{a=q, \bar{q}} f_a(x) D_g^h \left(\frac{\alpha_h}{x\zeta} \right) C_{qg}(x, \zeta) + \frac{C_A}{C_F} f_g(x) \sum_{a=q, \bar{q}} D_a^h \left(\frac{\alpha_h}{x\zeta} \right) C_{gq}(x, \zeta) \right] \right\}. \end{aligned} \quad (7)$$

The explicit form of the coefficient functions C_{ij} is given in our paper [4].

SUMMARY

We have calculated the NLO impact factor for the forward production of an identified hadron from an incoming quark or gluon, emitted by a proton. This is a necessary ingredient for the calculation of the hard inclusive production of a pair of rapidity-separated identified hadrons in proton collisions (1). This process, similarly to the production of Mueller-Navelet jets, can be studied at the LHC hadron collider.

Another natural application of the obtained identified hadron production IF could be the NLA BFKL description of inclusive forward hadron production process in DIS,

$$e(p_1) + p(p_2) \rightarrow h(k) + X, \quad (8)$$

where in the low- x event the hadron $h(k)$ with high transverse momentum is detected in the fragmentation region of incoming proton $p(p_2)$. Data for such reaction in the case of forward π^0 -production were published by the H1 collaboration at HERA [7].

In our approach the energy scale s_0 (which enters (4)) is an arbitrary parameter, that need not be fixed at any definite scale. The dependence on s_0 will disappear in the next-to-leading logarithmic approximation in any physical cross section in which the identified-hadron production vertices are used. Indeed, due to discussed above subtraction of the central rapidity gluon emission, our result for the NLO vertex contains contributions $\sim \ln(s_0)$,

$$C_{\{gg\},\{qq\}}(x, \zeta) = \delta(1 - \zeta) C_A \ln \left(\frac{s_0 \alpha_h^2}{\bar{k}_h^2 x^2} \right) \chi(n, \nu) + \dots$$

Note that these terms are proportional to the LO quark and gluon vertices multiplied by the BFKL kernel eigenvalue $\chi(n, \nu)$. This fact guarantees the independence of the identified-hadrons (1) or single-hadron (8) cross section on s_0 within the next-to-leading logarithmic approximation. However, the dependence on this energy scale will survive in terms beyond this approximation and will provide a parameter to be optimized with the method adopted in Refs. [8, 9].

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